Fifth-Year Response to Thinning in a Water Oak Plantation in North Louisiana

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ABSTRACT: *A 21 ac, 28-yr-old water oak (Quercus nigra L.) plantation, on an old-field loessial site in north Louisiana, was subjected to three thinning treatments during the winter of 1987–1988: (1) no thinning, (2) light thinning to 180 dominant and codominant trees/ac, and (3) heavy thinning to 90 dominant and codominant trees/ac. Prior to thinning, the plantation averaged 356 trees/ac and 86 ft²/ac of basal area, with a quadratic mean diameter of 6.7 in. Thinning reduced stand basal areas to 52 and 34 ft²/ac for the light and heavy thinning treatments, respectively. After 5 yr, both thinning treatments increased diameter growth rates of individual residual trees, both when all trees were considered and when the analysis was limited to dominant and codominant trees only. Neither thinning treatment affected either stand-level volume growth or total yield 5 yr after treatment. However, thinning distributed total volume growth among fewer trees, such that, when trees of all crown classes were considered in the analysis, average annual volume growth per tree increased with increasing intensity of thinning. Both basal area growth and volume growth following light thinning appear to be sufficient to promote rapid recovery of the stand to a fully stocked condition in the near future. In contrast, heavy thinning reduced density to a severely understocked condition that will prohibit optimum occupancy of the site for a long period. Among the treatments evaluated in this study, light thinning produced the most desirable combination of individual-tree diameter growth and stand-level basal area growth. South. J. Appl. For. 25(1):31–39.*

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Thinning regulates stand density and increases diameter growth of residual trees. Thinning in natural stands has improved the diameter growth of individual trees in a variety of hardwood forest types, such as Appalachian hardwoods (Lamson et al. 1990), Allegheny cherry-maple (*Prunus* spp.–*Acer* spp.) forests (Lamson 1985, Lamson and Smith 1988), and upland oak stands in the Central Hardwood Region (Hilt 1979, Sonderman 1984). Diameter growth response of residual trees increases with increasing intensity of thinning. However, very heavy thinning may lower stand density to the point where basal area growth and volume growth of the residual stand are greatly reduced, and recovery of the stand to a fully stocked condition is much delayed. Recommended minimum residual stocking levels necessary to maintain

satisfactory stand-level growth and to ensure full occupancy of the site for sawtimber production are 46–65% in upland oaks (Hilt 1979) and 45–60% in cherry-maple stands (Lamson and Smith 1988).

Information is sparse on the response to thinning in natural stands of southern bottomland hardwoods. Johnson (1968) reported that medium thinning to a basal area of about 70 ft²/ac produced the best combination of stand-level and tree-level volume growth in a 75-yr-old stagnated sweetgum (*Liquidambar styraciflua* L.) stand in Louisiana. Lighter thinning resulted in equivalent total volume growth of the stand, but also produced the lowest growth rate per tree because the total growth was distributed over more trees. Heavier thinning produced the highest growth per tree, but the residual stand was too sparse to fully utilize the site, and stand volume growth per acre was unacceptably low for profitable sawtimber production. Similarly, McGarity (1979) found that thinning to a basal area of about 66 ft²/ac in a young sweetgum stand proved to be superior to heavy thinning to 45 ft²/ac of basal area in terms of higher per-tree volume growth while maintaining good diameter growth of individual trees. Low thinning to a basal area of 72 ft²/ac in a 65-yr-old sugarberry (*Celtis laevigata* Willd.) stand in the Mississippi

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Delta approximately doubled the diameter growth rate of residual upper-crown-class trees 5 yr after thinning (Meadows et al. 1985).

General guidelines on thinning in natural stands of southern bottomland hardwoods are available, but they are based more on observations and experience than on research results (McKnight 1958, Meadows 1996, Goelz and Meadows 1997). These guidelines are useful to some extent, but to effectively manage southern bottomland hardwood forests for high-quality sawtimber production, land managers need specific, quantitative guidelines that include recommendations on the timing and intensity of thinning as well as marking rules that regulate the distribution of the cut and determine the structure of the residual stand.

Information on the growth and development of southern oak plantations greater than 20 yr of age is similarly lacking. Most past research on oak plantations concentrated on the development of suitable techniques for successful plantation establishment (Allen and Kennedy 1989, Kennedy 1993), but growth was generally followed for only a few years after establishment. Consequently, information on growth and yield, pattern of stand development, and the response of older plantations to intermediate silvicultural operations, such as thinning, is sparse.

With the creation of the Conservation Reserve Program (CRP) in 1985 and, more recently, the Wetland Reserve Program (WRP), many thousands of acres of marginal cropland in the South have been reforested, primarily to various oak species (Kennedy 1990). As these new oak plantations develop and mature, there will be an increasing demand for information on how to manage them. Land managers need practical guidelines on thinning and other intermediate silvicultural operations. Unfortunately, individual-tree and stand-level responses to thinning in oak plantations are largely unknown, and few guidelines currently exist for successful management of these older plantations.

This article presents the results of a thinning study that was established in the winter of 1987–1988 in two 28-yr-old water oak plantations in northern Louisiana. The objective of the study was to determine the diameter growth response of water oak to three thinning treatments. Stand parameters of the plantations 1 yr prior to treatment were previously described by Krinard and Johnson (1988). Fourth-year response to thinning was reported by Meadows and Goelz (1993).

Methods

Study Area

Two plantations were established in February 1960 on old agricultural fields of loessial soil on the Macon Ridge landform just east of Winnsboro, Louisiana. The fields had been under continuous cultivation for several decades prior to the establishment of the oak plantations. The surrounding fields remain in cultivation, primarily for the production of cotton and soybeans. The plantations encompass a total of 21 ac (a 14.5 ac tract and a nearby 6.5 ac tract). Three replications of the study, each comprising about 4.5 ac, were established within the larger tract, and one replication was established

within the smaller tract. Both tracts are privately owned. The landowner's objective in establishing these plantations was to maximize economic returns from the production of high-quality oak sawtimber. Both fields were planted at the rate of approximately 950 water oak seedlings per acre. Initial spacing was variable, but appears to have averaged 9 × 5 ft. No cultivation or other means of weed control was performed after planting at either site.

Krinard and Johnson (1988) described the soils at both sites as mixtures of Calhoun, Calloway, and Loring series, all of which developed from wind-blown silt, or loess. Calloway and Loring soils both contain fragipans at depths of 20–30 in. Texture in the upper soil horizons at both sites is either silt loam or silty clay loam. Soil pH is strongly acid and ranges from 4.5 to 5.0 across both sites. Productivity is moderately low for the growth of hardwoods on these loessial soils of the Macon Ridge when compared to well-drained bottomlands. Broadfoot (1976) reported an average site index of 83 ft at 50 yr for water oak on Calloway soils, but did not provide similar information for Calhoun or Loring soils. Using the method described by Baker and Broadfoot (1979), site index for water oak was estimated to average 86 ft at 50 yr across the entire study area.

Treatments and Measurements

In fall 1986, the plantation was divided into 12 treatment plots, 9 on the larger tract and 3 on the smaller tract. Each treatment plot was 150 ft by about 400–450 ft and covered an area of about 1.4 to 1.5 ac. Three 0.1 ac square measurement plots were systematically established within each of the 12 treatment plots; data were pooled across these 3 measurement plots within each treatment plot. Diameter breast height (dbh) and crown classes were assessed on all trees within each measurement plot. Stocking percent was estimated from trees per acre and quadratic mean diameter, using a stocking equation developed by Goelz (1995):

$$S = 0.01373T + 0.00960TD + 0.00378TD^2$$

where

S = stocking percent

T = trees per acre

D = quadratic mean diameter (in.)

Total height was measured on a subsample of 21–24 trees within each treatment plot. Total height of the other trees within each treatment plot was estimated from a height over dbh curve of the form:

$$\ln(\text{height}) = b_0 + b_1(1/\text{dbh})$$

Estimates of b_0 and b_1 were developed separately for each of the 12 treatment plots.

Krinard and Johnson (1988) formulated a local volume equation for water oak from sectional measurements of the boles of 20 water oak trees felled within the plantation in 1986:

$$V = 0.000718D^{1.677282}H^{1.450080}$$

where

V = total stem volume outside bark from a 1 ft stump to the tip (ft^3)

D = diameter breast height (in.)

H = measured or estimated total height (ft)

Fit index (a goodness-of-fit measure similar to r^2) of this local volume equation was 0.92 (Krinard and Johnson 1988). Under the assumption that the relationships between volume and diameter and height changed little during the 5 yr after thinning, we chose to use the equation developed by Krinard and Johnson (1988) for unthinned stands to estimate volume (ft^3/ac) at each measurement period for each of the 12 treatment plots, rather than use a generic, regional volume equation.

Thinning treatments were originally scheduled for the winter of 1986–1987, but wet soils prevented any harvesting activities. Height and dbh were not remeasured prior to thinning. Consequently, pretreatment measurements were actually taken 1 yr prior to treatment. In the winter of 1987–1988, at age 28, three thinning treatments were applied to the 12 treatment plots:

1. CONTROL—no thinning;

2. LIGHT—thin to 180 dominant and codominant trees/ac;

3. HEAVY—thin to 90 dominant and codominant trees/ac.

In both thinning treatments, low thinning was used to remove trees primarily from the lower crown classes. The study was measured immediately after thinning and has been measured annually for 5 yr. Height measurement and volume estimation were performed before treatment, immediately after treatment, and in the third and fifth years after treatment only. Although important, information on bole quality and epicormic branching of residual trees was not collected during the study. We also failed to record information on the presence of volunteer stems in the plantation and were unable to assess quantitatively the role of volunteers in competition with the planted trees.

Statistical Analysis

The study consisted of four replications of three thinning treatments applied in a randomized block design to 12 treatment plots (experimental units). Because many of the variables of interest were measured annually for the 5 yr period following treatment, we tested the hypothesis of no treatment effect by conducting analysis of variance using a repeated measures model (Neter et al. 1990) for the following variables: (1) trees per acre, (2) stand basal area, (3) stocking percent, (4) quadratic mean diameter, and (5) cumulative diameter growth. Repeated measures analysis of variance allowed detection of differences among treatments for any particular year of the study and also tested for differences among treatments in the response trend across time (indicated by a significant year-by-treatment interaction term). All tests were conducted using an *alpha* of 0.05. Treatment means were separated through use of Tukey's studentized range test for each year.

Because height measurement and subsequent volume estimation were not performed at constant time intervals, we used simple analysis of variance to detect differences among treatments in total height and stand volume before treatment, immediately after treatment, and 3 and 5 yr after treatment, as well as treatment differences in both height and volume growth. Diameter distributions and crown class distributions are presented graphically for each treatment. No statistical analyses were performed on these two variables.

To gain a better understanding of the effects of the thinning treatments on those trees most likely to become final crop trees, we assessed diameter and volume responses of the dominant and codominant trees only. Simple analysis of variance was used to detect differences among treatments in quadratic mean diameter, cumulative diameter growth, stand volume, and annual volume growth of this dominant/codominant component 5 yr after treatment.

Results

Residual Stand Conditions

Prior to thinning, the plantation averaged 356 trees/ac and 86 ft^2/ac of basal area, with an average total height of 54 ft, and a quadratic mean diameter of 6.7 in. Stocking averaged 87% across the entire plantation, and total volume averaged 2,150 ft^3/ac. No significant differences in any of these stand parameters were detected among the treatment plots 1 yr prior to thinning. Although no quantitative data were collected, general observations indicated that the density of volunteer stems of various species was low and that volunteer trees had little effect on the development of the planted water oaks.

Light thinning reduced stand density to 188 trees/ac and 52 ft^2/ac of basal area; heavy thinning reduced stand density to 103 trees/ac and 34 ft^2/ac of basal area. Volume in the lightly thinned plots was reduced from 2,104 to 1,316 ft^3/ac, whereas volume in the heavily thinned plots was reduced from 1,963 to 810 ft^3/ac. Expressed as percentages, light thinning removed about 52% of the trees, 39% of the basal area, and 37% of the volume from the plantation, whereas heavy thinning removed about 70% of the trees, 59% of the basal area, and 59% of the volume. Light thinning reduced stocking to 52% of maximum full stocking; heavy thinning reduced stocking to 33% of maximum full stocking. Maximum full stocking, delineated as 100% stocking, is defined as the heaviest stocking in which individual trees can maintain good diameter growth under intensive management (Putnam et al. 1960). It represents a situation in which full site occupancy has been achieved and a thinning operation is warranted to maintain good growth (Goelz and Meadows 1997).

Because low thinning was used to remove the smaller, less vigorous trees, primarily from the lower crown classes, quadratic mean diameter in the thinned plots was higher immediately after thinning than in those same plots before thinning. Quadratic mean diameter in the lightly thinned plots increased from 6.3 in. 1 yr prior to thinning to 7.1 in. immediately following thinning, whereas quadratic mean diameter in the heavily thinned plots increased from 6.7 in. to 7.8 in. after thinning. Quadratic mean diameter in the unthinned

Table 1. Changes in the number of trees per acre, by treatment, following thinning in a 28-yr-old water oak plantation. Means followed by the same letter are not significantly different at the 0.05 level of probability.

Treatment	1 yr before harvest	After harvest	1 yr	2 yr	3 yr	4 yr	5 yr
Unthinned	336 a	319 a	293 a	282 a	271 a	270 a	268 a
Light thin	392 a	188 b	180 b	179 b	179 b	178 b	178 b
Heavy thin	340 a	103 c	102 c	100 c	100 c	100 c	99 c

plots was initially high (7.3 in.), such that no significant differences in quadratic mean diameter were detected among the three treatments after thinning.

Stand Development Following Thinning

Stand development during the 5 yr period following thinning was characterized by high mortality in the unthinned plots and by steady recovery in the thinned plots. One of the most striking developments has been the steady decline in the number of trees per acre in the unthinned plots, dropping from 319 at the time of study installation to 268 in 5 yr (Table 1). This decrease is equivalent to 16% mortality over the 5 yr period. In contrast, mortality in the thinned plots has been substantially less, about 5% and 4% 5 yr after light and heavy thinning, respectively. Mortality in the unthinned plots occurred primarily in the smaller, less vigorous, lower crown class trees, and may have provided some degree of temporary, partial release from competition for adjacent surviving trees. On the other hand, low thinning removed large numbers of these same types of trees in one operation rather than gradually over time. Thus, the removal of anticipated mortality through thinning provided much greater relief from competition to the residual trees than the gradual process of natural mortality could provide to surviving trees in the unthinned plots.

Both light and heavy thinning substantially reduced stand basal area, to 52 and 34 ft²/ac, respectively. However, during the 5 yr period following thinning, basal area increased steadily to 70 and 48 ft²/ac in the lightly and heavily thinned stands, respectively (Table 2). During the same period, basal area in the unthinned stand increased from 92 to 105 ft²/ac. Analysis of cumulative stand-level basal area growth over the 5 yr period following thinning revealed no statistical differences among the three treatments. However, repeated measures analysis of variance detected a significant year-by-treatment interaction term, indicating that the rate of basal area growth over the 5 yr period did differ among treatments. In fact, stand basal area growth rates averaged 3.6, 2.8, and 2.6 ft²/ac/yr in the lightly thinned, heavily thinned, and unthinned stands, respectively. If these basal area growth rates continue, we expect to find significant treatment differences in cumulative basal area growth in the near future.

A similar trend was observed for changes in stocking percent among the three treatments over the 5 yr period following thinning (Table 3). Light thinning reduced stocking to 52%, a value consistent with the suggested residual stocking level after

thinning in natural stands of similar density and average tree size, as recommended by Putnam et al. (1960), and as represented by a B-line stocking of approximately 50–55% (Goelz 1995). The B-line in a stocking guide represents minimum stocking for full site utilization and generally is viewed as an index of minimum full stocking, while 100% stocking is typically regarded as an index of maximum full stocking. On the other hand, heavy thinning reduced stocking to 33%, a value well below recommended residual density after thinning in southern bottomland hardwoods (Putnam et al. 1960, Goelz 1995). Five years after thinning, stocking in the lightly thinned stand rose to 65%, adequate stocking to promote good stand-level growth and recovery from thinning disturbance. However, stocking in the heavily thinned stand increased to only 43% 5 yr after thinning, a level still well below recommended stand density (Putnam et al. 1960, Goelz 1995). Even 5 yr after thinning, the heavily thinned stand is still severely understocked. In comparison, stocking in the unthinned stand averaged 91% at the time of treatment, and increased to 99% over the 5 yr period, values still slightly below maximum full stocking of 100%.

Prior to thinning, the diameter distribution of the water oak plantation resembled a bell-shaped curve in which the most abundant diameter class was 6 in. (Figure 1). Five years after study installation, the greatest abundance of trees in the unthinned stand occurred in both the 7 and 9 in. diameter classes. In contrast, heavy thinning removed many trees from the lower diameter classes and caused a shift in peak abundance to a higher diameter class, while light thinning had little effect on diameter distribution other than to reduce the number of trees in each diameter class. In general, diameter distributions of single-species, even-aged stands flatten and shift to the right as the stand develops and matures. Consequently, heavy thinning has, at least temporarily, increased the rate of stand development in this water oak plantation.

Prior to thinning, 74% of the trees in the water oak plantation were classed as either dominant or codominant (Figure 2a). However, in just 5 yr, the proportion of upper crown class trees in the unthinned stand dropped dramatically to only 47%, indicative of a stand experiencing much competition and considerable canopy stratification. In absolute terms, the number of upper crown class trees per acre in the unthinned stand dropped from 265 to 126 during the same period (Figure 2b). Crowns of individual trees in the unthinned stand are deteriorating, losing dominance, and experiencing

Table 2. Changes in stand basal area (ft²/ac), by treatment, following thinning in a 28-yr-old water oak plantation. Means followed by the same letter are not significantly different at the 0.05 level of probability.

Treatment	1 yr before harvest	After harvest	1 yr	2 yr	3 yr	4 yr	5 yr
Unthinned	90 a	92 a	93 a	95 a	100 a	104 a	105 a
Light thin	85 a	52 b	54 b	57 b	63 b	67 b	70 b
Heavy thin	83 a	34 c	36 c	38 c	43 c	46 c	48 c

Treatment	1 yr before harvest	After harvest	1 yr	2 yr	3 yr	4 yr	5 yr
Unthinned	90 a	91 a	90 a	91 a	94 a	97 a	99 a
Light thin	88 a	52 b	52 b	55 b	60 b	63 b	65 b
Heavy thin	84 a	33 c	34 c	36 c	39 c	42 c	43 c

diminished photosynthetic capacity, a situation leading to reduced tree growth, increased mortality, and possibly reduced stand productivity. In contrast, both thinning treatments removed trees primarily from the lower crown classes and produced stands that, at least so far, have been able to maintain high proportions of upper crown class trees: 70% in the lightly thinned stand and 81% in the heavily thinned stand (Figure 2a). Five years after thinning, the density of upper-crown-class trees was 124 trees/ac in the lightly thinned stand and 80 trees/ac in the heavily thinned stand (Figure 2b). Although the numbers of dominant and codominant trees were similar in the unthinned stand (126 trees/ac) and the lightly thinned stand (124 trees/ac), the rate of decline in the density of upper crown class trees was much greater in the unthinned stand than in either of the thinned stands. For example, from the end of the third year to the end of the fifth year after treatment, there was a loss of 21 trees/ac from the upper crown classes in the unthinned stand, as compared to losses of 13 trees/ac and 10 trees/ac in the lightly thinned and heavily thinned stands, respectively. Although crown subordination of a few scattered trees is occurring in the thinned stands, it is not as widespread as in the unthinned stand. In fact, the proportion of upper crown class trees in the heavily thinned stand 5 yr after thinning is still higher than in the pretreatment stand, a situation perhaps reflective of the understocked condition of the heavily thinned stand. Both thinning treatments have maintained or enhanced vigor of most trees, at least through 5 yr, as evidenced by both high proportions and high numbers of upper crown class trees.

Diameter Growth

We were unable to detect any statistical differences among the treatments in quadratic mean diameter during the 5 yr period following thinning (Figure 3). However, repeated measures analysis of variance did reveal a significant year-by-treatment interaction term, indicating that the rate of

change in quadratic mean diameter differed significantly among the three treatments. Quadratic mean diameter of the heavily thinned stand is increasing at a more rapid pace than in either the lightly thinned or the unthinned stands. Heavy thinning increased quadratic mean diameter by 1.6 in., to 9.4 in. in the 5 yr following thinning; increases in quadratic mean diameter of 1.4 and 1.2 in. were observed in the lightly thinned and unthinned stands, respectively, over the same period. Because the rate at which quadratic mean diameter is changing differed among treatments (as evidenced by the significant year-by-treatment interaction), we expect to find significant differences in quadratic mean diameter between the thinned and unthinned stands in the near future.

However, changes in quadratic mean diameter are not completely indicative of diameter growth, particularly in dense, unthinned stands. The 5 yr increase in quadratic mean diameter observed in the unthinned stand was at

Figure 2. Pooled crown class distribution 1 yr prior to thinning and the crown class distributions produced through each treatment 5 yr after thinning in a 28-yr-old water oak plantation, in terms of (a) the proportion of trees in each crown class and (b) the actual number of trees per acre in each crown class.
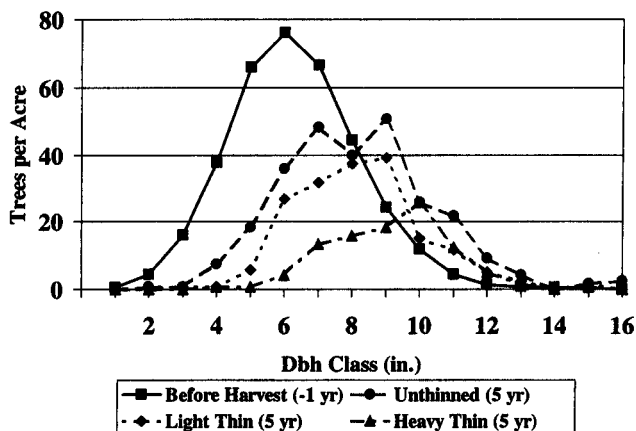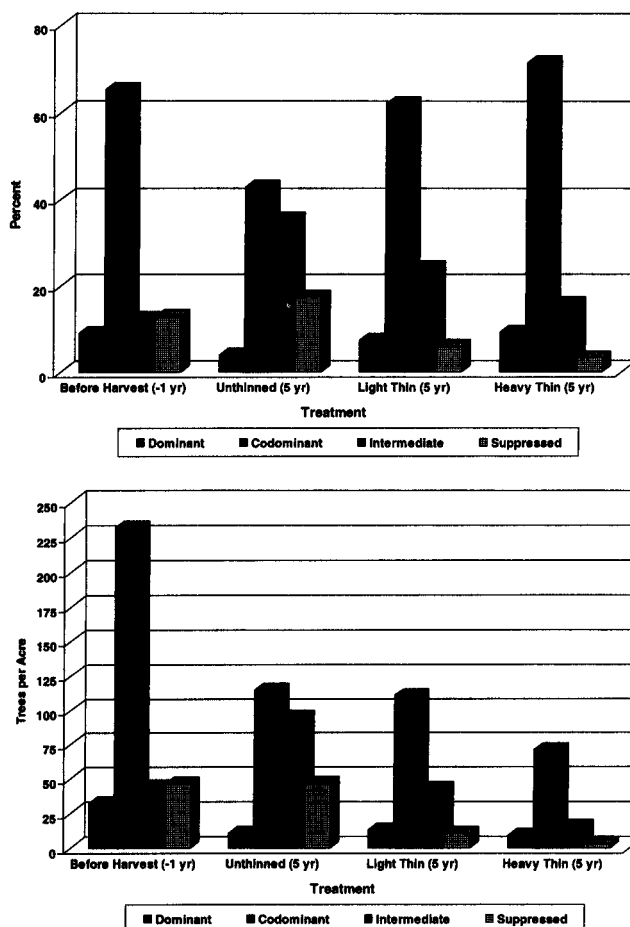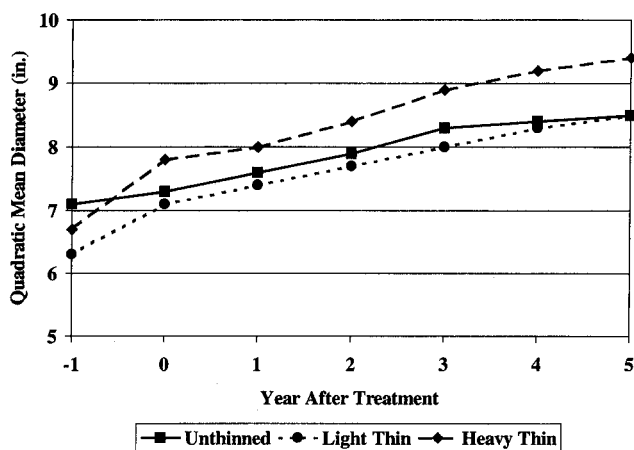

Figure 1. Pooled diameter distribution 1 yr prior to thinning and the diameter distributions produced by each treatment 5 yr after thinning in a 28-yr-old water oak plantation.

Figure 3. Changes in quadratic mean diameter, by treatment, following thinning in a 28-yr-old water oak plantation.

Figure 4. Cumulative diameter growth of residual trees, by treatment, following thinning in a 28-yr-old water oak plantation.

least partially due to mortality of small trees in addition to actual diameter growth of surviving trees. Consequently, quadratic mean diameter in the unthinned stand was somewhat inflated by the death of small trees. On the other hand, quadratic mean diameter in the unthinned stand was also somewhat deflated by the continued presence of many small trees. These confounding influences on quadratic mean diameter may mask important differences among treatments in individual-tree diameter growth.

Cumulative diameter growth of individual trees may provide a more accurate assessment of the effects of the thinning treatments (Figure 4). Neither thinning treatment had an effect on individual-tree cumulative diameter growth during the first 2 yr after thinning, with growth averaging about 0.44 in. across all treatments. However, a response to thinning was detected during the third year, when cumulative diameter growth of residual trees in heavily thinned plots was significantly greater than in unthinned plots. This trend continued through the fourth and fifth years, in which ever-widening significant differences were found between the thinned and unthinned treatments. By the end of the fifth year after thinning, surviving trees in the unthinned stand had grown an average of only 0.83 in. in diameter. Such poor growth is indicative of a low-vigor stand, in which additional mortality of small trees should be expected in the near future. On the other hand, residual trees in the lightly thinned stand grew an average of 1.27 in. in 5 yr, whereas residual trees in the heavily thinned stand grew an average of 1.54 in. in 5 yr. Five-year cumulative diameter growth did not differ significantly between the two thinning treatments, but both produced cumulative diameter growth significantly greater than that
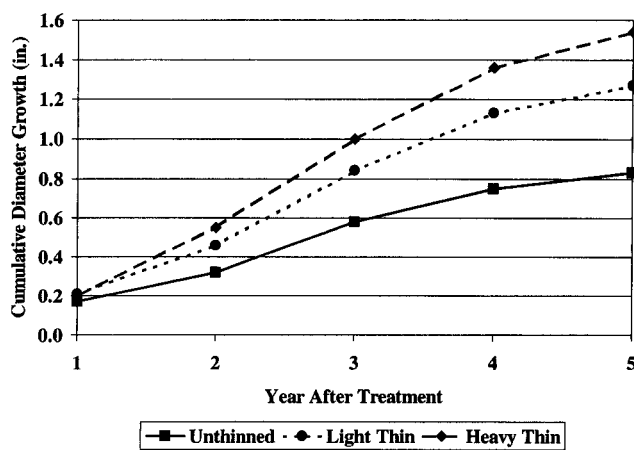
observed in the unthinned stand after 5 yr. We anticipate that these differences in diameter growth rate will continue over the next several years.

Volume Growth

Ultimately, the success of these thinning treatments will be judged by their effects on stand volume, volume growth, and yield (Table 4). Prior to thinning, stand volume averaged 2,150 ft³/ac across the entire plantation, with no significant differences among treatment plots. Light thinning removed 788 ft³/ac, about 37% of the volume, to a residual volume of 1,316 ft³/ac; heavy thinning removed 1,153 ft³/ac, about 59% of the volume, to a residual volume of only 810 ft³/ac. By the end of the fifth year after treatment, volume in the unthinned stand increased 27% to over 3,000 ft³/ac, whereas volumes in both thinned stands were still below their prethinning values and were much less than the volume in the unthinned stand.

Although thinning created significant differences among treatments in stand volume that persisted through the first 5 yr after treatment, thinning had no significant effects on either stand-level volume growth or total yield during the same period (Table 4). Within very wide limits of residual stand density, thinning generally does not affect total cubic foot volume production of a stand. Consequently, both stand volume growth and total yield (existing stand volume plus the volume removed) were similar across the three treatments in this water oak plantation. However, because stand-level volume growth was distributed among fewer trees in the thinned stands, average annual volume growth per tree increased with increasing intensity of thinning—from 0.48 ft³/yr in the unthinned stand to 0.60 ft³/yr in the lightly thinned stand to 0.80 ft³/yr in the heavily thinned stand.

Table 4. Stand volume, yield, and average annual volume growth, by treatment, following thinning in a 28-yr-old water oak plantation. Means followed by the same letter are not significantly different at the 0.05 level of probability.

Treatment	Stand volume					Volume growth	
	Before harvest	Removed	After harvest	5 yr	Yield	Annual growth (ft³/ac/yr)	Growth per tree (ft³/yr)
	·· (ft³/ac)··						
Unthinned	2,382 a	0 b	2,382 a	3,027 a	3,027 a	129 a	0.48 b
Light thin	2,104 a	788 a	1,316 b	1,850 b	2,638 a	107 a	0.60 ab
Heavy thin	1,963 a	1,153 a	810 c	1,206 c	2,359 a	79 a	0.80 a

Growth of Dominant/Codominant Component

Most of the lower crown class trees are not expected to develop into high-quality sawtimber trees. Many of them are likely to die from suppression before the end of the rotation. Those that survive will likely remain in a subordinate canopy position and will be marketed as pulpwood. Because the management objective is to produce high-quality oak sawtimber, the landowner is not very interested in the long-term growth of these lower crown class trees. Their potential value is much less than the potential value of the upper crown class trees in the plantation. Therefore, to evaluate more accurately the effects of the thinning treatments on those trees of greatest interest to the landowner, we assessed diameter and volume responses of the dominant and codominant trees only.

Thinning did not increase the quadratic mean diameter of the dominant/codominant component of the plantation (Table 5). In fact, quadratic mean diameter within the lightly thinned stand was significantly lower than in both the unthinned and heavily thinned stands. In contrast, when trees of all crown classes were considered, quadratic mean diameter did not differ among the three treatments (Figure 3).

However, both thinning treatments increased 5 yr cumulative diameter growth of individual dominant and codominant trees, but no significant differences between the two levels of thinning could be detected (Table 5). Upper crown class trees in the heavily thinned stand grew 1.63 in. in diameter in 5 yr, whereas those in the lightly thinned stand grew 1.45 in. Dominant and codominant trees in the unthinned stand grew only 1.13 in. in 5 yr. Similar results were found when trees of all crown classes were considered (Figure 4). This poor diameter growth within the dominant/codominant component of the unthinned stand will likely lead to further reductions in the density of upper crown class trees as marginally healthy trees drop to the intermediate and suppressed classes. Continued poor diameter growth of dominant and codominant trees in the unthinned stand is expected to continue in the future, such that the differences in diameter growth between the unthinned and thinned stands will likely continue to widen. In fact, because 5 yr cumulative diameter growth of individual dominant and codominant trees in the heavily thinned stand was much greater than that found within the unthinned stand, we expect that the quadratic mean diameter of the dominant/codominant component of the heavily thinned stand will eventually surpass that of the unthinned stand.

Differences in volume within the dominant/codominant component were created through the thinning operation; these differences persisted through the first 5 yr after treatment (Table 5). Similar results were found when trees of all crown classes were considered (Table 4). Even though both

total stand volume and the volume within just the dominant/codominant component were greater in the unthinned stand than in either of the thinned stands, the proportion of the total volume contained in upper crown class trees was greater in the thinned stands. Dominant and codominant trees accounted for 83% of the total volume in the lightly thinned stand and 90% of the total volume in the heavily thinned stand, whereas only 67% of the total volume in the unthinned stand was distributed among upper crown class trees. Consequently, both thinning treatments allowed a much greater proportion of the total wood production of the stand to be concentrated in those trees most likely to produce high-quality sawtimber as final crop trees.

Thinning had no significant effects on the average annual volume growth rate of the dominant/codominant component, when calculated on either a per-acre or a per-tree basis (Table 5). Better than 90% of the total stand volume growth accrued on dominant and codominant trees, regardless of treatment. Consequently, average annual volume growth per tree within the dominant/codominant component was uniform across all treatments. In contrast, when trees of all crown classes were considered, average annual volume growth increased significantly with increasing intensity of thinning (Table 4) because stand-level volume growth was distributed among fewer trees in the thinned stands.

Discussion

Trees in the unthinned stand are not currently growing in diameter at an acceptable rate for water oak. Expressed on a 10-yr basis, dominant and codominant trees are growing at the rate of 2.3 in. per decade. Upper crown class water oak trees should be expected to maintain diameter growth rates of 3 in. per decade or greater (Putnam et al. 1960). Most are trees in the unthinned stand currently in subordinate crown classes and, if left unmanaged, will continue to decline in growth, vigor, and quality. Mortality, particularly of the lower crown class trees, will likely continue to be high in the next several years. Current stocking in the unthinned stand is 99%, just below the point of maximum full stocking (100%). When stocking exceeds 100%, which will likely occur within the next year, the unthinned stand will be classed as overstocked. As a result of this high stocking level, current conditions within the unthinned stand are not favorable for the development of vigorous, high-quality water oak trees. If the overstocking is not alleviated through thinning in the near future, the health of even dominant and codominant trees will deteriorate, crowns will become even more crowded, and the competitive ability of individual trees will diminish. Reduced tree growth and increased mortality will occur as the

Table 5. Diameter and volume responses of the dominant/codominant component of a 28-yr-old water oak plantation 5 yr after thinning. Means followed by the same letter are not significantly different at the 0.05 level of probability.

Treatment	Quadratic mean diameter	Cumulative diameter growth	Stand volume (ft³/ac)	Volume growth (ft³/ac/yr)	Volume growth per tree (ft³/yr)
	(in.)				
Unthinned	10.0 a	1.13 b	2,030 a	116 a	0.92 a
Light thin	9.2 b	1.45 a	1,534 b	102 a	0.82 a
Heavy thin	9.8 a	1.63 a	1,080 c	74 a	0.93 a

stand stagnates. At its current rate of growth and development, we estimate that the dominant/codominant component of the unthinned stand will reach small sawtimber size (quadratic mean diameter of 14 in.) in another 18–20 yr, or at about age 51–53.

Among the treatments evaluated in this study, light thinning produced the most desirable combination of individual-tree diameter growth and stand-level basal area growth and volume growth. Light thinning increased average diameter growth rate of residual dominant and codominant trees to an acceptable level of 2.9 in. per decade. Stand-level basal area growth and volume growth appear to be sufficient to promote recovery of the stand to maximum full stocking in a reasonable period of time. In the absence of further management, we estimate that the dominant/codominant component of the lightly thinned stand will reach small sawtimber size in another 15–17 yr, or at about age 48–50. However, we also estimate, based on its current rate of development, that this stand will achieve maximum full stocking when quadratic mean diameter of the entire stand (when trees of all crown classes are considered) reaches about 11 in., which will occur in another 10 yr, or at about age 43. A low thinning at age 43 will shorten the time required for the dominant/codominant component to reach small sawtimber size. Additional thinnings will likely be necessary before the end of a sawtimber rotation.

Heavy thinning increased average diameter growth rate of residual dominant and codominant trees to 3.3 in. per decade, a growth rate 44% higher than that observed in the unthinned stand. However, heavy thinning reduced stocking to the point that stand-level basal area growth and volume growth are inadequate to allow full recovery of the stand in the near future. At its present rate of growth, we estimate that the dominant/codominant component of the heavily thinned stand will reach small sawtimber size in another 10–12 yr, or at about age 43–45. However, because heavy thinning initially created a severely understocked condition (33% stocking), this stand will likely not achieve maximum full stocking until quadratic mean diameter of the entire stand reaches about 15 in., which we estimate will occur in another 18 yr, or at about age 51. Although heavy thinning greatly increased diameter growth of residual trees, it created a severely understocked stand that will not achieve maximum full stocking for a total of about 23 yr after the initial thinning. Consequently, for many years, the heavily thinned stand will be unable to fully occupy the site and to fully realize the site's potential productivity.

The inability of the residual trees to respond more positively to thinning was at least partially due to the relatively poor site and its moderately low productivity. Growth of the planted water oaks was restricted by a combination of poor drainage, low-to-medium fertility, past land use, and the presence of fragipans on portions of the study site. A fragipan greatly limits tree growth because it results in a perched high water table during winter and spring, but constricts the effective rooting depth and leads to severe water deficits during summer. This situation, coupled with the poor drainage and slow permeability of the soil above the fragipan, creates a harsh site that is very wet in the winter and spring and very dry in the summer and fall. Although thinning alleviated some of the competition for soil moisture and nutrients, the inherent low productivity of the site itself limited the ability of the residual trees to respond to the thinning.

The diameter growth response to thinning was also diminished as a consequence of the narrow initial spacing that led to a relatively long period of intense competition prior to thinning in the water oak plantation. Average initial spacing (9 × 5 ft) was too narrow to allow satisfactory development of individual trees for sawtimber management. The narrow spacing led to the onset of intense competition among neighboring trees, particularly within rows where average distance between trees was only 5 ft. Trees severely competed with one another for soil moisture, nutrients, light, and growing space for several years prior to thinning. As a result, many of the surviving trees in the stand at the time of thinning were small, low-vigor trees with narrow, deteriorating crowns, poor bole quality, and less than satisfactory diameter growth rates.

The presence of many dead trees scattered throughout the plantation and the presence of numerous epicormic branches along the boles of many of the living trees indicated that the plantation was not healthy and was approaching stagnation. When grown in even-aged mixtures with sweetgum, bottomland red oaks are generally able to gain a competitive advantage over the sweetgum, dominate the stand, and develop into large trees with long, clear boles (Clatterbuck 1987, Clatterbuck and Hodges 1988, Johnson and Krinard 1988). However, oaks do not compete well with other oaks when grown in pure stands (Aust et al. 1985). It is difficult for individual oaks to gain a competitive advantage over neighboring oaks. Consequently, pure oak stands, such as this water oak plantation, tend to stagnate quickly after several years of intense competition among individual trees.

These three factors, a relatively poor site, narrow initial spacing, and the inability of oaks to compete well with other oaks when grown in pure stands, combined to produce a plantation composed largely of low-vigor trees. In many hardwood species, trees growing under such stressful conditions have a tendency to produce epicormic branches along the bole. Although we did not quantitatively assess the degree of epicormic branching in this study, we observed that there were numerous epicormic branches along the boles of many of the water oak trees in the plantation prior to thinning. Water oak is highly susceptible to epicormic branching (Meadows 1995), particularly when the trees are stressed, and is therefore at great risk of producing new epicormic branches following any type of stand disturbance. Consequently, when the water oak plantation was thinned, the increased sunlight triggered the production of many new epicormic branches along the boles of the residual trees. Because the defects caused by epicormic branches greatly reduce the grade and subsequent value of the lumber produced from the tree, the presence of numerous epicormic branches on a majority of the trees creates a very undesirable situation in stands managed for the production of high-quality sawtimber.

Recommendations

To alleviate the problems of overcrowding and early stagnation, we currently recommend that initial spacing in bottomland red oak plantations range from 8 × 9 ft to 11 × 12 ft, depending on anticipated survival of planted trees and expected availability of markets for the small-diameter trees to be removed during the first thinning (Goelz and Meadows 1997). Nearly square spacing is preferable to rectangular spacing because it promotes the development of symmetrical crowns and it leads to a more even distribution of competitive pressure from surrounding trees. Rectangular spacing, on the other hand, allows the onset of competition from adjacent trees to occur at an earlier age (along the narrow side of the rectangle) and thus promotes the development of asymmetrical crowns. We also encourage landowners to consider establishing red oaks in mixed-species plantations, particularly in mixture with sweetgum, rather than in pure oak plantations. Individual oaks surrounded by sweetgum are in a much better competitive situation than are oaks surrounded by other oaks. However, there are many cases in which pure oak plantations have already been established with narrow initial spacing, such as the water oak plantation considered in this study. In this situation, the landowner may need to consider some type of remedial action to alleviate the over-crowding before stand stagnation begins (even if stocking is less than 100%). Precommercial thinning may be required to create conditions more amenable to the management goal of high-quality sawtimber production.

Ideally, an oak plantation established at a square or nearly square initial spacing within the recommended range can be thinned commercially when maximum full stocking of 100% is reached. Average stand diameter at the time of this first thinning will be approximately 8 in. (Goelz and Meadows 1997). We recommend the use of low thinning to remove selectively the less vigorous, lower crown class trees to a target residual stocking level of about 50–60%. This level of thinning would remove about 50% of the trees and about 40–45% of the basal area. A lighter thinning would not adequately release potential crop trees from surrounding competition. At residual stocking levels greater than 60% after the first thinning, stand-level growth would be satisfactory, but individual tree growth would be less than desirable. A heavier thinning, such as the one evaluated in this study, would remove so many trees that the plantation would underutilize the site for many years. At residual stocking levels less than 50% after the first thinning, individual-tree growth would be satisfactory, but stand-level growth would be less than desirable. A compromise must be sought to produce the most desirable combination of individual-tree diameter growth and stand-level basal area growth and volume growth. On good sites, the thinned plantation should recover to near 100% stocking in approximately 10–15 yr following the first thinning. As the plantation develops and matures, subsequent thinnings should generally become lighter in intensity as target residual stocking levels increase (Goelz 1995).

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